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Carbon Sequestration and Permit Trading on the Competitive Fringe

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Communalism versus the Incentive to Free-Ride: Experimental Results from Economically Emergent Africa

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Communalism versus the Incentive to Free-Ride: Experimental Results from Economically Emergent Africa

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ABSTRACT

This paper makes two contributions to the carbon-sequestration literature. The first is the development of a theoretical framework within which sequestration and permit trading may be analyzed jointly in the context of a competitive fringe model. The second is a numerical analysis of the model. We find that when the cost-structure changes lead to progressively less separation in costs between the competitive fringe and the polluters (as well as between the polluters themselves), and the dominant firm becomes progressively more low-cost relative to the competitive fringe and the polluters, the equilibrium allocations of seqùestration and abatement align with a higher carbon price. Aggregate output from the competitive fringe decreases smoothly and asymptotically toward zero. However, the (implied) number of fringe firms fluctuates up and down, eventually reaching zero itself. This type of result demonstrates the importance of incorporating into empirical supply-side models demand-side information that is reflective of an underlying market structure.

Keywords: carbon sequestration; competitive fringe; abatement credits

JEL Classification: D43, L13, Q54

Carbon Sequestration and Permit Trading on the Competitive Fringe

Abstract

This paper makes two contributions to the carbon-sequestration literature. The first is the development of a theoretical framework within which sequestration and permit trading may be analyzed jointly in the context of a competitive fringe model. The second is a numerical analysis of the model. We find that when the cost-structure changes lead to progressively less separation in costs between the competitive fringe and the polluters (as well as between the polluters themselves), and the dominant firm becomes progressively more low-cost relative to the competitive fringe and the polluters, the equilibrium allocations of sequestration and abatement align with a higher carbon price. Aggregate output from the competitive fringe decreases smoothly and asymptotically toward zero. However, the (implied) number of fringe firms fluctuates up and down, eventually reaching zero itself. This type of result demonstrates the importance of incorporating into empirical supply-side models demand-side information that is reflective of an underlying market structure.

1. Introduction

The main focus of carbon sequestration research has thus far been the empirical estimation of supply functions, both for specific countries and globally.[1] Although the supply estimates themselves vary, the general opinion emerging from this literature is that scope exists for cost-effective policies fostering both the curtailment of deforestation and promotion of reforestation in support of carbon sequestration at national, regional, and international levels. What has not yet been considered in this analysis, however, is the role that market structure, or market power, might play in the determination of an equilibrium sequestration allocation and associated carbon price. This paper is a first attempt at characterizing the role of market structure in the context of a carbon sequestration model that also incorporates permit trading, and is thus in keeping with multi-instrument approaches promulgated in international agreements such as the Kyoto Protocol (UNFCCC, 1998).

A similar issue was faced roughly 20 years ago with respect to permit trading, when Hahn's (1984) seminal article demonstrated the importance of market power in determining an equilibrium outcome. Hahn's principle result was that if a single firm with market power purchases(sells) permits in an otherwise competitive market it will behave as a monopsonist(monopolist). Thus, the degree of market inefficiency is systematically related to the initial distribution of the permits. Since then, research has attempted to quantify the extent to which monopoly and monopsony power influence the

[1] With respect to country-specific studies, see Stavins (1999) and Lubowski, et al. (2006) for the US, Xu (1995) for China, Fearnside (1995) for Brazil, Ravindranath and Somashekhar (1995) for India, de Jong, et al. (2000) for Mexico, and Sedjo (1999) for Argentina. See Benitez, et al. (2007) and Sohngen and Sedjo (2004) for estimates of global supply.

permit-trading equilibrium, most notably in the field of experimental economics using auction-type environments.[2]

Contrary to these earlier works, which assume the existence of monopoly and monopsony power, we develop a competitive fringe model that reflects the most likely structure that will emerge in a global market (or series of regional markets) for carbon sequestration in the presence of permit trading. Our presumption that a competitive fringe will emerge in the sequestration market is premised on two strands of the sequestration literature. The first strand is empirical, the second theoretical.

With respect to the empirical literature, Benitez, et al. (2007) estimate global sequestration supply curves for afforestation and reforestation activities based on highly disaggregated (grid-level) physical data with country-level controls for political, financial, and economic risks. They find that low-cost sequestration sites are mainly located in regions of the developing world, such as Sub-Saharan Africa, southeastern Brazil, and Southeast Asia.[3] This suggests *inter alia* that national-level findings, most notably those of Stavins (1999) and Lubowski, et al. (2006), must be tempered by the fact that domestic sequestration policies are likely to co-exist, be supplemented by, or be pre-empted by international or regional agreements to combat climate change. As a result of comparative advantages, such as those identified by Benitez, et al. (2007), the equilibrium that emerges in a regional or global sequestration may be governed more by the interplay of a dominant firm (or nation or region) and a competitive fringe than by perfect competition within a given nation.

[2] See Muller, et al. (2002) and Godby (2000) for examples of this strand of the experimental literature.
[3] Sohngen and Sedjo's (2004) numerical analysis of global sequestration potential is not as sanguine about the extent of these regional comparative advantages.

It is of course possible that on a global scale the market for sequestration could resemble more an oligopoly than a competitive fringe. However, as Asheim, et al. (2006) point out, there are fairly general conditions under which multiple regional agreements (that internalize global externalities such as climate change) outperform a single global agreement. In particular, the authors find that a regime with two agreements can Pareto dominate a regime based on a single global treaty, implying that regional cooperation might be a good alternative – or supplement – to a global environmental agreement. In a world governed by such regional agreements oligopolies are less likely to form.

Consider, for example, a regional agreement between the US and Brazil. Brazil, for its part, could potentially act as a dominant firm due to its relatively low marginal costs of sequestration (associated with existing reforestation opportunities on vast tracts of public land (Benitez, et al., 2007)). US farmers would in turn act as a competitive fringe due to their relatively high marginal costs of sequestration (associated with existing opportunity costs for alternative private land uses (Lubowski, et al., 2006)). International trading in sequestered carbon would complement an existing domestic permit-trading market in the US that includes the nation's largest industrial polluters.

In this paper, we develop a simple theoretical framework of a competitive sequestration fringe in conjunction with a permit trading market (for abatement by polluters). We then demonstrate through numerical analysis the responsiveness of equilibrium sequestration and abatement to changes in the relative cost structures of the three agents included in the model – a dominant sequestration firm, competitive fringe firms, and polluters who participate in a permit trading market. We find that when the cost-structure changes lead to progressively less separation in costs between the competitive fringe and the polluters (as well as between the polluters themselves), and the dominant firm becomes progressively more low-cost relative to the competitive fringe and the polluters, the equilibrium allocations of sequestration and abatement align with a higher carbon price. Aggregate output from the competitive fringe decreases smoothly and asymptotically toward zero. However, the (implied) number of fringe firms fluctuates up and down, eventually reaching zero itself.

We begin our analysis in Section 2 with a simple graphical exposition of the competitive fringe model in the presence of permit trading. Section 3 provides a more rigorous mathematical framework and presents a simple numerical model, which is then solved for an initial set of parameter values and for subsequent changes in the relative cost structures embodied by these parameters. The results of the numerical analysis are discussed in Section 4. Section 5 summarizes and concludes.

2. A Simple Graphical Analysis

This section presents a simple graphical analysis of sequestration and permit trading in the context of a competitive fringe model. As a point of departure, consider the standard textbook model of the competitive fringe depicted in Figure 1.[4]

[INSERT FIGURE 1 HERE]

In this figure, residual demand for the dominant firm's output, D^r, is the horizontal difference between market demand, D, and the aggregate supply of the (competitive) fringe firms, $S^f = MC^f$ (the kink in D^r occurs precisely at the vertical intercept of S^f). The dominant firm maximizes profit at point d, by setting a price of p^* and selling q_d^* units

[4] This particular model is adopted from Carlton and Perloff (2004).

(where MR^r intersects MC^r). The competitive fringe therefore produces q_f^* at point *f* and market equilibrium occurs at point *e*, with price p^* and total quantity $Q^* = q_f^* + q_d^*$.

Incorporating permit trading into this model (for ease of exposition only two polluters cum traders are needed) adds corresponding kinks to the dominant firm's residual demand curve. The model is depicted in Figure 2.

[INSERT FIGURE 2 HERE]

In Figure 2, the D^r curve has kinks at prices p_f (the vertical intercept of the competitive fringe's aggregate supply curve S^f) and p_1 (the vertical intercept of polluter *p1*'s permit supply curve S^{p1}). Here, the dominant firm maximizes profit at point *e* by setting a price of p^* and selling q_d^* units of sequestered carbon. The competitive fringe therefore produces q_f^* of sequestration at point *d* and polluter *p1* offers q_{p1}^* abatement credits for sale at point *f* (via abatement beyond its statutorily required amount). Because the equilibrium price p^* lies beneath the vertical intercept of its permit supply curve, polluter *p2* chooses not to supply a positive amount of abatement credits to the market.[5] Market equilibrium occurs at point *g*, with price p^* and total quantity sequestered $Q^* = q_{p1}^* + q_f^* + q_d^*$.

Figure 2 brings to light a complication in the sequestration/permit trading model that is absent from the basic model depicted in Figure 1. In Figure 1, closure (via equating market demand and supply) is not really an issue. This is because the demand and supply

[5] Note that the vertical intercept of D^r occurs at price p_2, which in turn is the vertical intercept of polluter *p2*'s permit supply curve S^{p2}. The coincidence of these two vertical intercepts is consistent with the fact that for carbon prices above p_2 polluter *p2* also becomes a net supplier of abatement credits. With both polluters *p1* and *p2* now being net suppliers, market demand for sequestration is effectively negative, i.e., for prices above p_2 the D^r curve extends into the second quadrant of the Cartesian coordinate system.

sides of the market are separate, i.e., those demanding the good are not also supplying it, and vice versa. This is not the case in the sequestration/permit trading model.

Recall from Figure 2 that polluter *p1* is a net supplier of abatement credits, and both the competitive fringe and dominant firm are also suppliers of credits (in the form of sequestration). Because it is explicitly included in the model, polluter *p2* must therefore consume the total amount of credits produced for sale, Q^*. This explains the positioning of polluter *p2*'s permit supply curve. The equilibrium price p^* is consistent with polluter *p2* effectively supplying a negative amount of abatement credits for sale (i.e., demanding a positive number of credits). In specific, polluter *p2*'s demand for credits must equal the total amount of credits offered for sale by the dominant firm, the competitive fringe, and polluter *p1*, i.e., Q^*.

To provide a more rigorous assessment of the competitive fringe/permit trading model, in particular with respect to its comparative static properties, we now turn to theoretical and numerical analyses based on a full accounting of the model's components. In particular, we explicitly close the model with a market-clearing condition that is premised on statutorily required abatement levels for each polluter.

3. Theoretical and Numerical Models

As indicated in Section 2, the competitive fringe model of carbon sequestration and permit trading has three different types of agents/industries: (i) a dominant firm, (ii) a permit-trading market comprised of polluting firms, and (iii) a competitive fringe. We begin this section with a general analytical treatment of sequestration and permit trading, which then guides the development of a simple numerical model to assess the responsiveness of sequestration and abatement to changes in the relative cost structures of the three agents/industries.

To begin, the dominant firm chooses its quantity of carbon sequestration, q_d, to solve the profit-maximization problem,[6]

$$\text{Max}_{q_d} \pi_d = p\left(q_d, \boldsymbol{q}_p^*, q_f^*\right) q_d - c_d\left(q_d\right) - F_d$$

where p is the per-unit price of sequestered carbon (also, in equilibrium, the price of a carbon permit), $\boldsymbol{q}_p^*$ is the vector $\left(q_{p1}^*, \ldots, q_{pI}^*\right)$ of (profit-maximized) net supplies of abatement credits produced by the $i = 1, \ldots, I$ polluting firms participating in the permit market ($q_{pi}^* \gtreqless 0$ for all i), $q_f^* = \sum_j q_{fj}^*$ is the total (profit-maximized) supply of sequestered carbon produced by the $j = 1, \ldots, J$ competitive fringe firms ($q_{fj}^* \geq 0$ for all j), c_d is the dominant firm's sequestration (total) cost function ($c_d' > 0, c_d'' > 0$), and F_d is a one-time licensing fee verifying the transferability of the dominant firm's sequestered carbon.[7] Further, p_{q_d}, $p_{\boldsymbol{q}_p^*}$, and $p_{q_f^*}$ are each assumed negative.[8]

The Kuhn-Tucker optimality condition for this problem is,

$$p_{q_d}(\cdot) q_d + p(\cdot) \leq c_d'(\cdot)$$

which results in the dominant firm's implicit supply of carbon sequestration,

$$q_d^* = q_d\left(\boldsymbol{q}_p^*, q_f^*\right) \geq 0 \tag{1}$$

---

[6] Variables preceding the parentheses are functions of the variables included within the parentheses. The $'$ and $''$ superscripts represent the first and second partial derivatives, respectively, of the sole variable included in the function, and a subscripted variable indicates a partial derivative with respect to the variable in the subscript.

[7] We assume a long-run equilibrium is established in the model. Accordingly, fixed costs of sequestration and abatement do not exist. The one-time licensing fee, F_d, is therefore assumed independent of the dominant firm's scale.

[8] As a result of these curvature conditions on c_d and p, the dominant firm's problem is concave.

and, for future reference, partially determines the equilibrium price of sequestered carbon, p^*.

In the permit trading market, polluter i chooses its quantity of abatement, $\tilde{q}_{pi}$, to solve the following cost minimization problem,

$$\text{Min}_{\tilde{q}_{pi}} c_{pi}(\tilde{q}_{pi}) - p^*(\tilde{q}_{pi} - \bar{q}_{pi}), \quad i = 1,....,I$$

where c_{pi} is polluter i's abatement cost function ($c'_{pi} > 0, c''_{pi} > 0$), $\bar{q}_{pi}$ is polluter i's statutorily required abatement level, and $\bar{Q}_p = \sum_i \bar{q}_{pi}$.[9] Note that polluter i takes p^* as given in this problem.

The Kuhn-Tucker optimality conditions for this problem are,

$$c'_{pi}(\cdot) \leq p^*, \quad i = 1,....I$$

which result in the polluters' implicit abatement functions,

$$\tilde{q}^*_{pi} = \tilde{q}_{pi}(p^*) \geq 0, \quad i = 1,....,I$$

and implicitly defines the corresponding net abatement supply functions,

$$q^*_{pi} = q_{pi}(p^*, \bar{q}_{pi}) = \tilde{q}^*_{pi} - \bar{q}_{pi}, \quad i = 1,....,I. \tag{2}$$

Polluters with $q^*_{pi} > 0$ ($q^*_{pi} < 0$) are net suppliers (buyers) of abatement. For future reference, let $Q^*_p = \sum_i q^*_{pi} \gtreqless 0$ refer to aggregate net abatement supply.

With respect to the competitive fringe, firm j chooses its quantity of carbon sequestration, q_{fj}, to solve the profit-maximization problem,

[9] The curvature conditions on c_{pi} ensure that the polluting firm's problem is concave. Note that this problem can equivalently be expressed in terms of the polluting firm's choice of emissions rather than abatement level. We have chosen the latter merely for expositional and numerical modeling convenience. Also for convenience, we assume that verifying the transferability of the polluters' abatement is costless.

$$\text{Max}_{q_{fj}} \pi_{fj} = p^* q_{fj} - c_{fj}(q_{fj}) - F_{fj},\ j = 1,\dots,J$$

where c_{fj} is fringe firm j's sequestration cost function ($c'_{fj} > 0, c''_{fj} > 0$), and (similar to the dominant firm) F_{fj} is a one-time licensing fee verifying the transferability of fringe firm j's sequestered carbon..[10] As in polluter i's cost minimization problem, fringe firm j takes p^* as given.

The Kuhn-Tucker optimality conditions for this problem are,

$$c'_{fj}(\cdot) \geq p^*,\ j = 1,\dots,J$$

which result in the fringe firms' implicit sequestration supply functions,

$$q^*_{fj} = q_{fj}(p^*) \geq 0,\ j = 1,\dots,J. \tag{3}$$

In long-run equilibrium the zero-profit condition for fringe firms j, $\pi^*_{fj} = 0$, determines the number of firms in the fringe,

$$n^*_f = n_f(p^*, \boldsymbol{F}_f) \geq 0 \tag{4}$$

where $\boldsymbol{F}_f = (F_1,\dots,F_J)$ is the vector of fringe firms' licensing fees.

Finally, a market clearing condition closes the model,

$$\overline{Q}_p \leq q^*_f + q^*_d + Q^*_p = Q^*. \tag{5}$$

Equation (5) states that aggregate sequestration from the dominant firm and the fringe firms, $q^*_d + q^*_f$, coupled with aggregate abatement from the polluting firms, Q^*_p, must be no less than aggregate statutorily required abatement, $\overline{Q}_p$. Equations (1) – (5) form a system of I + J + 3 equations that can be used to solve for the I + J + 3 equilibrium

[10] The curvature conditions on c_{fj} ensure that the fringe firm's problem is concave.

variables $\left(p^*, q_d^*, n_f^*, q_{fj}^*, q_{pi}^*\right)$, $i = 1,....,I$ and $j = 1,....,J$. In addition, a corresponding profit level for the dominant firm, $\pi_d^* \geq 0$, can be calculated.

For the numerical analysis of this model we first assume, as in Section 2, the existence of two polluters, *p1* and *p2*, and an endogenously determined number of competitive fringe firms, which in turn determine an aggregate fringe supply.[11] For simplicity, we use the zero-profit condition to implicitly determine the number of fringe firms in long-run equilibrium. This is accomplished by first aggregating the firms' marginal costs into an industry-level equivalent and then using the industry-level zero-profit condition to endogenize $F_f = \sum_j F_{fj}$. As a result, the zero-profit condition holds at the industry level and F_f serves as an implicit proxy for the actual number of fringe firms in long-run equilibrium, i.e., a larger value of F_f implies a larger n_f^*, all else equal. Also for simplicity, and without loss of generality, we assume that $F_d = vF_f$, where $v > 0$ is a proportionality factor, i.e., the dominant firm's licensing fee is proportionate to the competitive fringe's.

Cost functions for the dominant firm, the competitive fringe, and the polluters are each assumed quadratic.[12] Specifically,

$$c_d = \alpha_d q_d + \frac{q_d^2}{\varepsilon_d^2} + F_d$$

$$c_f = \alpha_f q_f + \frac{q_f^2}{\varepsilon_f^2} + F_f$$

---

[11] The numerical simulations are performed using GAMS, version 2.0.13.

[12] This functional form is consistent with both Lubowski, et al. (2006) and Benitez, et al. (2007). Lubowski, et al. (2006) estimate a logistic aggregate supply (marginal cost) function, to which the linear marginal cost function of the quadratic specification provides a fairly close approximation. Our linear marginal cost function also approximates quite closely the quadratic function estimated in Benitez, et al. (2007) over the majority of the range of carbon sequestration considered in that study.

$$c_{pi} = \alpha_{pi}\tilde{q}_{pi} + \left(\beta_{pi}\tilde{q}_{pi}\right)^2, \ i = 1,2.$$

where cost parameters α_d, α_f, α_{pi}, and β_{pi} and output elasticities ε_d and ε_f are each greater than zero, $i = 1,2$ (the remaining variables were previously defined above). It is important to note that α_{pi} is not the vertical intercept of polluter i's abatement-credit supply curve, e.g., it is not equal to p_i (from $MC^{pi} = S^{pi}$, $i = 1,2$) in Figure 2. The vertical intercept for credit supply is instead $\alpha_{pi} + 20\beta_{pi}$, which is the first partial of c_{pi} evaluated at $\tilde{q}_{pi} = \bar{q}_{pi} = 10$ (i.e., where q_{pi} equals zero), $i = 1,2$.

Initial values for each parameter in the model are presented in Table 1. Note that these values distinguish polluter $p2$ as being high-cost (in terms of marginal abatement cost) relative to polluter $p1$. Polluter $p2$ is also high-cost relative to the dominant firm and the competitive fringe. However, the slope of polluter $p1$'s marginal cost curve ($2\beta_{p1}$ = 0.5) is less than the corresponding slope of the competitive fringe's aggregate marginal cost ($2/\varepsilon_f^2 = 2$), while its vertical intercept (α_{p1} =0.015) is slightly larger (α_f = 0.01). Both the competitive fringe and polluter $p1$ are high-cost relative to the dominant firm. These relative costs reflect the underlying maintained assumptions of the competitive fringe model, in particular that the dominant firm generally faces lower sequestration costs than the competitive fringe and the polluters, and the competitive fringe in turn faces lower cost than at least some of the polluters.[13]

[INSERT TABLE 1 HERE]

Since the demand curve facing the dominant firm has a total of three kink points (including the vertical intercept), one each corresponding to the vertical intercepts of the

[13] In order to focus attention on the role of divergent abatement cost structures, we assume equivalent required abatement levels for the polluters, i.e., $\bar{q}_{p1} = \bar{q}_{p2} = 10$.

marginal sequestration/abatement-credit cost curves for the competitive fringe, α_f, and the two polluters, $\alpha_{pi} + 20\beta_{pi}$, $i = 1,2$, we run three separate constrained versions of the model: (i) $p^* \leq \alpha_f$, (ii) $\alpha_f < p^* \leq \alpha_{p1} + 20\beta_{p1}$, and (iii) $\alpha_{p1} + 20\beta_{p1} < p^* < \alpha_{p2} + 20\beta_{p2}$, (reference the residual demand curve D^r in Figure 2). The version of the model associated with the highest profit for the dominant firm then represents the equilibrium solution. In the case of this particular numerical analysis, model version (iii) is associated with the dominant firm's highest profit level. This is the region of residual demand where the carbon price is least restricted on the upside.

To assess the responsiveness of sequestration and abatement to changes in the relative cost structures of the three agents/industries, we introduce step increases (up to 10 separate steps) in the slope parameters of the two polluters, β_{p1} and β_{p2}, and step decreases (of the same magnitude) in the elasticity parameter of the competitive fringe, ε_f. The step increases(decreases), μ, are each of the same magnitude, μ=0.1(-0.1) Thus, for example, in the first step ε_f decreases from one to 0.9, β_{p1} increases from 0.25 to 0.35, and β_{p2} increases from two to 2.1. In the second step ε_f decreases from 0.9 to 0.8, β_{p1} increases from 0.35 to 0.45, and β_{p2} increases from 2.1 to 2.2, and so on. These steps lead to progressively less separation in costs between the competitive fringe and the polluters, as well as between polluters *p1* and *p2* themselves. In particular, polluter *p2* becomes proportionately less high-cost relative to polluter *p1*, and both polluters become proportionately less high-cost relative to the competitive fringe. The competitive fringe and the polluters in turn become progressively more high-cost relative to the dominant firm (in terms of the rate of change in marginal sequestration cost).

4. Numerical Results

Table 2 presents our numerical results based on the initial parameter values contained in Table 1. The second column in the table presents the benchmark equilibrium for the case of perfect competition, where the dominant firm does not exist and the market is therefore supplied solely by the competitive fringe (and any abatement credits contributed by the two polluters).[14] The table's third column presents results for the competitive fringe model (i.e., with the dominant firm included).

[INSERT TABLE 2 HERE]

We begin by noting that at these initial parameter values the competitive fringe produces slightly less sequestration in aggregate than the dominant firm, i.e., $q_d^* = 3.441 > q_f^* = 3.014$. At the equilibrium price $p^* = 6.039$, polluter *p1* supplies a positive amount of abatement credits ($q_{p1}^* = 2.048$), while polluter *p2* demands the sum of these credits and the sequestration produced by the dominant firm and competitive fringe, i.e., $\bar{q}_{p2} - \tilde{q}_{p2} = Q^* = 8.503 \Rightarrow q_{p2}^* = -8.503$.

As expected, in relation to the competitive benchmark equilibrium the competitive fringe's supply of sequestration, as well as both polluters' abatement efforts, all decrease in response to the presence of a dominant firm. The equilibrium carbon price also decreases, due to the combination of the dominant firm's lower costs of sequestration and the restriction of the market demand curve (see Figure 2). The decrease in the

[14] The conception of perfect competition in the competitive fringe model is markedly different than in a monopoly model. In a monopoly model, the monopolist's marginal cost curve corresponds to (or is subsumed by) the industry's marginal cost under perfect competition. As a result of this difference, the equilibrium carbon price in the competitive fringe model can be higher than in the perfect competition model.

(endogenized) licensing fee for the competitive fringe, F_s^*, indicates that the equilibrium number of fringe firms decreases in the presence of a dominant firm.

Figures 3 and 4 show how the initial equilibrium in the competitive fringe model changes as the parameter values β_{p1}, β_{p2}, ε_f are changed. As described in Section 3, these changes lead to progressively less separation in costs between the competitive fringe and the polluters, as well as between polluters *p1* and *p2* themselves. Polluter *p2* becomes proportionately less high-cost relative to polluter *p1*, and both polluters become proportionately less high-cost relative to the competitive fringe. The competitive fringe and the polluters in turn become progressively more high-cost relative to the dominant firm.

[INSERT FIGURES 3 AND 4 HERE]

In Figure 3 we see that these changes result in both the competitive fringe and low-cost polluter *p1* losing market share to the dominant firm. The competitive fringe loses market share at an increasing rate up to the sixth step increase in its marginal cost, at which point its sequestration supply begins an asymptotic decent toward zero. Polluter *p1* loses market share at a decreasing rate throughout and becomes a net buyer of sequestration at the fourth step increase in its marginal abatement cost. These two trends position the dominant firm as the sole supplier of sequestration (to both polluters) by the 10th step increase.

Concomitant with these changes in relative market shares, Figure 4 shows that the dominant firm's profit increases exponentially with the step increases. The carbon price rises along with the dominant firm's market share and profit (and the gradual disappearance of the competitive fringe). Interestingly, the (implied) number of fringe firms rises gradually over the first 5 step increases (approximately the same number of steps during which the fringe's (aggregate) market share declines at an increasing rate). The number of firms then falls for the next two periods, rises again for the following period, and then falls steeply toward zero by the final step. At that point the fringe has completely disappeared.

5. Summary and Discussion

This paper makes two contributions to the carbon-sequestration literature; a literature which has heretofore been focused on the empirical estimation of sequestration supply functions, both for specific countries and globally. The first contribution is to develop a theoretical framework within which sequestration and permit trading may be analyzed jointly in the context of a competitive fringe model. An empirically based motivation for developing this framework is provided by Benitez, et al. (2007), who find that low-cost sequestration sites are mainly located in regions such as Sub-Saharan Africa, southeastern Brazil, and Southeast Asia. This suggests that the equilibrium emerging in a regional or global sequestration market may be governed more by the interplay of a dominant firm (e.g., public land owned by a specific region or nation) and a competitive fringe (e.g., private land owned by U.S. farmers) than by perfect competition within a given nation (as assumed by Stavins (1999) and Lubowski, et al. (2006)).

The second contribution is to numerically analyze the competitive fringe/permit-trading model. We find that when the cost-structure changes lead to progressively less separation in costs between the competitive fringe and the polluters (as well as between the polluters themselves), and the dominant firm becomes progressively more low-cost relative to the competitive fringe and the polluters, the equilibrium allocations of sequestration and abatement align with a higher carbon price. Aggregate output from the competitive fringe decreases smoothly and asymptotically toward zero. However, the (implied) number of fringe firms fluctuates up and down, eventually reaching zero itself. These results demonstrate the responsiveness of sequestration and abatement allocations to changes in the relative cost structures of the dominant firm, the competitive fringe, and the polluters engaged in permit trading.

Of course numerical analysis based on ad hoc parameter values and functional forms is limited by its inability to inform policy with anything other than a more qualitative assessment of equilibrium allocations in a relative sense, e.g., by answering questions such as how 'smooth' might be the disappearance of a competitive fringe as the dominant firm becomes more cost-effective in its production of sequestration, or vice-versa? Until the parameter values and functional forms themselves are empirically estimated and incorporated into the numerical analysis, the numerical model will be limited in its policy relevance.

However, this type of criticism also runs in the opposite direction. Until empirical analyses such as Stavins (1999), Lubowski, et al. (2006), and Benitez, et al. (2007) account for both the global nature of the carbon sequestration problem and the corresponding market structures that are most likely to govern the behavior of the various agents involved, estimates of what are inherently endogenous variables (e.g., the allocation of sequestration and abatement and the carbon price) will be biased estimates of the equilibrium outcomes themselves. Thus, the avenue for future research seems clear.

Demand-side information must be incorporated into supply-side models; information that is global in scale (or regional if carbon emissions are to be controlled via a set of region-based agreements a la Asheim, et al., 2006) and reflective of underlying market structure. Incorporation of this type of information into national supply-side models, such as those of Lubowski, et al. (2006) and Stavins (1999), will extend supply estimates from reflecting what is possible under the parochial assumptions of perfect competition to what is a likely in the wider realm of a global equilibrium. The same can be said for global supply-side models, such as Benitez, et al.'s (2007). With respect to the role that market structure might play in the allocation of sequestration and abatement on a global or regional scale; echoes can be heard of Hahn's (1984) seminal article demonstrating the importance of market power in determining an equilibrium outcome.

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Figure 1. Standard Competitive Fringe Model.

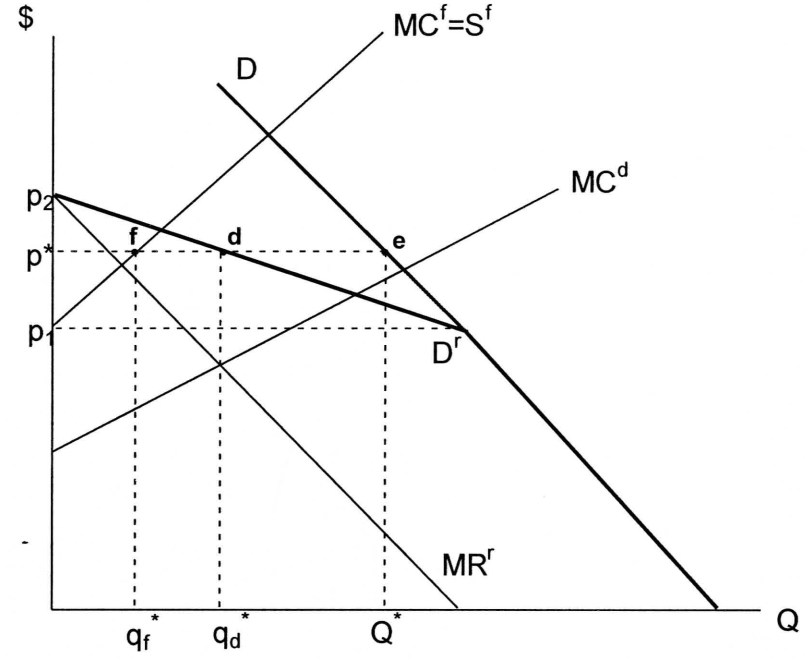

Figure 2. Competitive Fringe Model with Permit Trading.

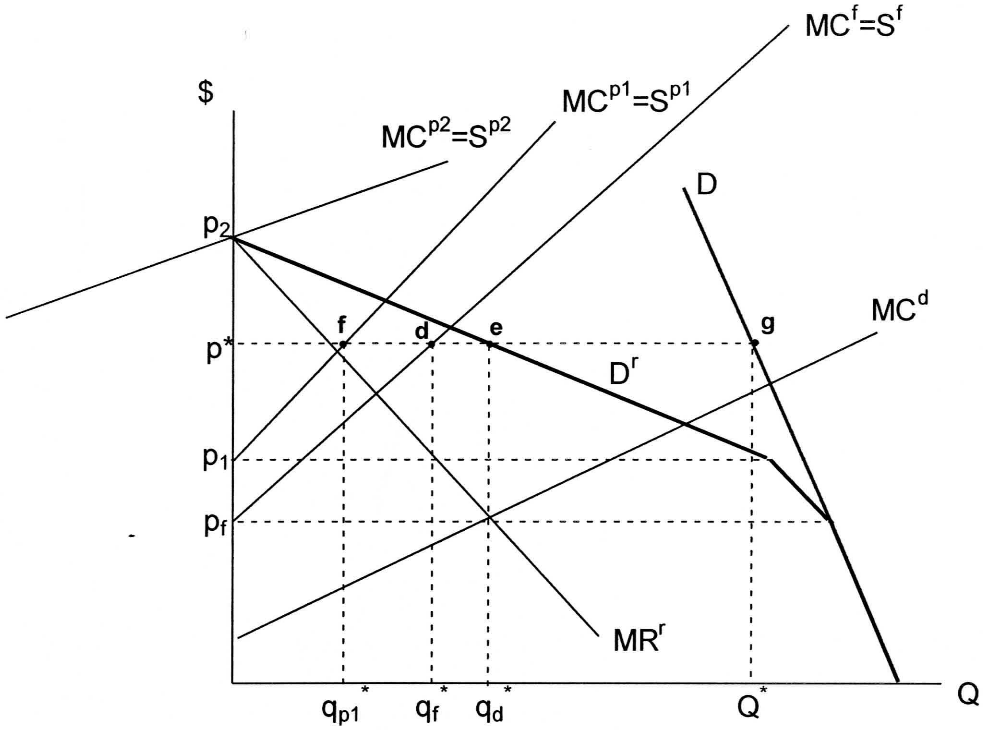

Figure 3. Quantities of Sequestration and Abatement Credits.

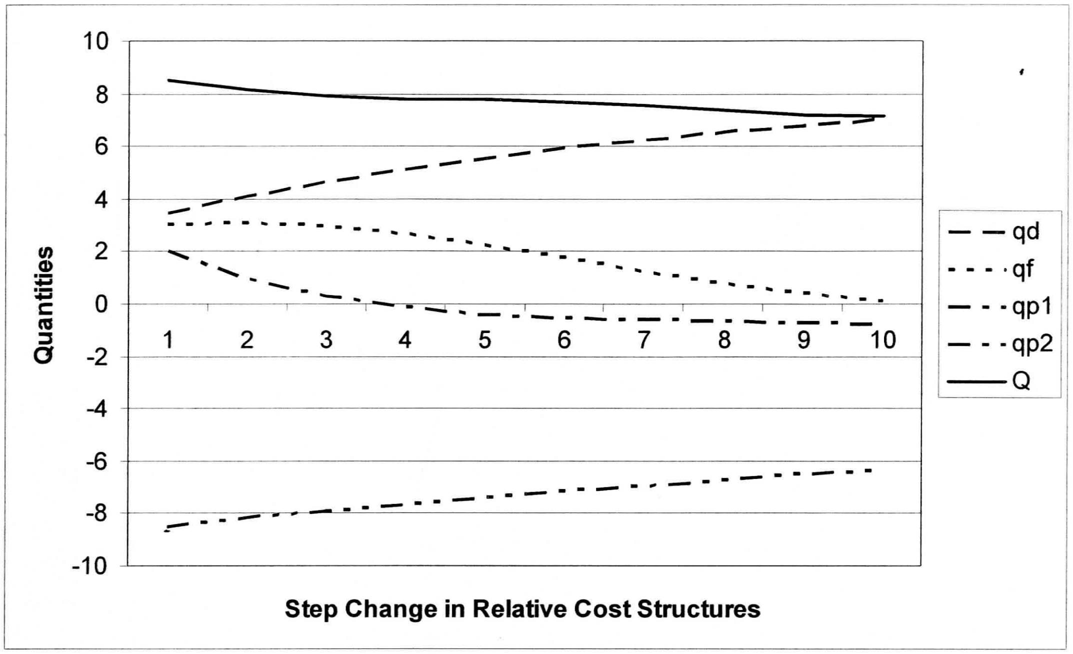

Figure 4. Carbon Price, Dominant Firm Profit, and Implicit Number of Fringe Firms.

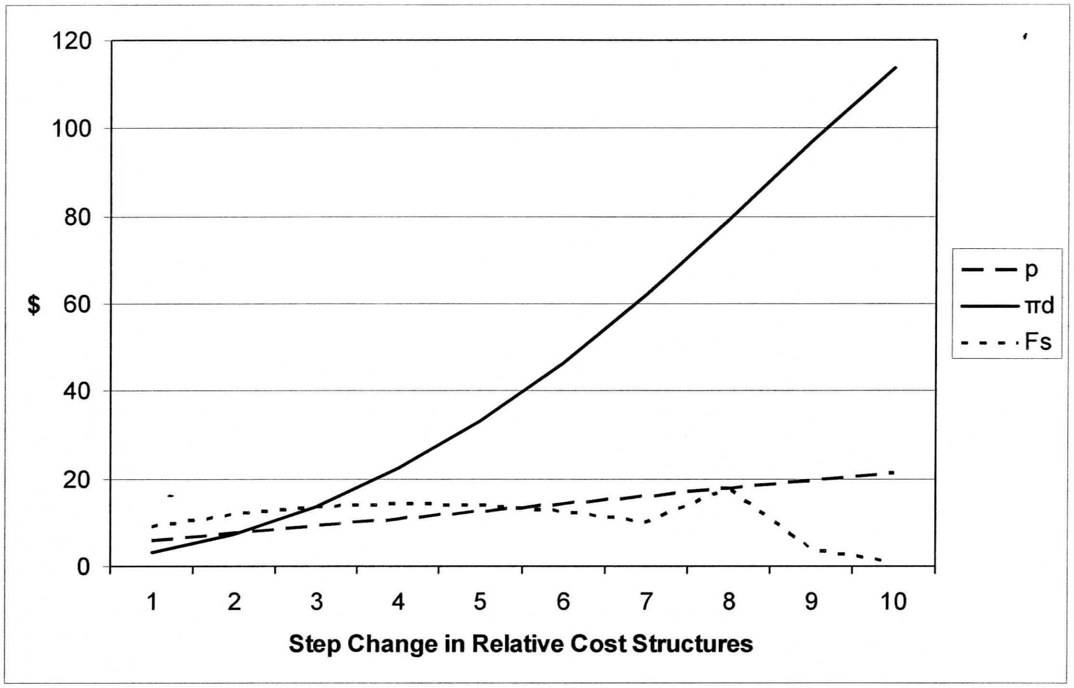

Table 1. Initial Parameter Values for Numerical Analysis.

Parameter	Initial Value
α_d	0.009
α_f	0.01
α_{p1}	0.015
α_{p2}	0.05
β_{p1}	0.25
β_{p2}	2.0
ε_d	1.2
ε_f	1
v	1.05
$\bar{q}_{p1}$	10
$\bar{q}_{p2}$	10

Table 2. Equilibrium Solutions Based on Initial Parameter Values.

Variable	Perfect Competition	Competitive Fringe
q_d^*	---	3.441
q_f^*	3.640	3.014
q_{p1}^*	4.550	2.048
q_{p2}^*	-8.190	-8.503
Q^*	8.190	8.503
p^*	7.290	6.039
π_d^*	---	2.985
F_s^*	13.250	9.087